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# RESEARCH MEMORANDUM

A BIBLIOGRAPHY OF NACA REPORTS ON CONTROL  
OF TURBOJET ENGINES

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INTRODUCTION

An annotated bibliography of NACA reports containing information of interest to designers and manufacturers of controls for turbojet engines is needed primarily because NACA reports are published as segments of information are discovered. Furthermore, many reports of interest are not found in a normal index because the title makes no specific reference to controls. This report therefore presents a listing of all NACA reports containing information pertinent to the control of turbojet engines.

This bibliography lists the reports under the eleven major topics, starting, acceleration, flame-out, temperature control, stability and dynamics of small disturbances, combustion dynamics, engine inlet diffuser control, steady-state engine performance, fuel systems, sensors, and general control system theory. Under each topic, mention is made of several problems that have been studied, and one or two appropriate reports are cited.

Listed under each topic are NACA reports containing information significantly related to the particular topic. In a few instances, references to periodical literature are made where the work is not available in NACA reports.

Documents in the NACA Report series (designated NACA Rep.) may be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D. C. Technical Notes (designated NACA TN), Research Memorandums (designated NACA RM), and the several professional society papers by NACA authors that are cited may be obtained from NACA Headquarters, 1512 H. Street, N. W., Washington 25, D. C.

STARTING

Some of the problems connected with starting that influence control design are (1) cranking, (2) windmilling, (3) ignition, (4) propagation of flame, (5) acceleration from cranking speed to operating speed, and (6) damage to engine incurred in starting.

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Some experimental observations of required cranking speed and starter power for a centrifugal turbojet engine are given by Koenig and Dandois (RM E7L17), but no reports on the general problems of cranking have been published. Windmilling characteristics of several engines are surveyed by Wallner and Welna (RM E51J23), and some general conclusions concerning windmilling are presented. The accessory drive power available in windmilling for one engine is shown by Walker and Fenn (RM E52D30).

Ignition characteristics are presented by Straight and McCafferty (RM E55G28) in a general survey. Fundamental factors influencing ignition are explored in a series of papers by Swett (RM's E9E17, E51J12, E52J28, E54F29a, and E55I16). Fuel-flow requirements for ignition of a turbojet engine are described by Rayle and Douglass (RM E50H16a). Ignitor-spark requirements are presented by Foster and Straight (RM E54A14), and design trends to improve ignition are discussed by Armstrong and Wilsted (RM E52I03). Effects of fuel-nozzle design and fuel-spray pattern on ignition are discussed in several reports, one of which is by Gold and Straight (RM E8D14). Effects of fuel volatility on ignition are presented by Braithwaite and Sivo (RM E53L11).

Factors affecting flame propagation from ignited combustors to adjacent unignited ones (including required fuel-flow manipulation) are given by Armstrong and Wilsted (RM E52I03). Acceleration characteristics, temperatures of turbine blades, and fuel-flow requirements for accelerating from ignition and cranking speed to a useful operating speed are presented by Phillips (RM E55L22). Flame-out encountered during acceleration to useful operating speed is shown by Golladay and Bloomer (RM E50G07).

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Sobolewski, Adam E., and Lubick, Robert J.: Altitude Operational Characteristics of Prototype J40-WE-8 Turbojet Engine. NACA RM E52L29, 1953.

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Straight, David M., and McCafferty, Richard J.: Turbojet Engine Starting and Acceleration. Ch. XI of Adaptation of Combustion Principles to Aircraft Propulsion, vol. II. NACA RM E55G28, 1956.

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Wilsted, H. Dean, and Armstrong, J. C.: Preliminary Results of Turbojet-Engine Altitude-Starting Investigation. NACA RM E51H30, 1951.

## ACCELERATION

## Characteristics

Acceleration from cranking speed to useful operating speed was investigated by Phillips (RM E55L22); acceleration in the useful operating range is discussed by Stiglic, Schmidt, and Delio (RM E54H24). In both these reports, maps showing speed, fuel flow, turbine discharge temperature, and acceleration are presented. The report by Phillips shows the transfer function of turbine blade temperature over the complete speed range, thereby making possible the estimation of transient blade temperatures in response to arbitrary manipulation of fuel flow. Acceleration characteristics of a single-spool turbojet engine are derived from component characteristics by Otto and Taylor (Rep. 1011). Acceleration of a two-spool turbojet engine as determined from component characteristics is presented by Dugan (RM E54L28).

Effects of altitude and flight Mach number on acceleration are described by Wallner and Lubick (RM E54I28). The variability of engine acceleration with engine overhaul and with different engines of the same model is shown by Wallner and Lubick (RM E54I28). The change of acceleration with rapidly repeated acceleration is demonstrated by Mallett and Groesbeck (RM E55G27). The effects of changes in the air-pressure profile at the compressor inlet was explored by Harry and Lubick (RM E54K26).

## Control

Schedules suitable for use in acceleration controls are discussed by Oppenheimer and Pack (RM E53H26). Compressor inlet-guide-vane adjustment was investigated by Dobson and Wallner (RM E54I30), and turbine-stator adjustment by Walker and Jansen (RM E54G26a). The effectiveness of compressor inlet baffles in suppressing rotating stall is discussed by Huntley, Huppert, and Calvert (RM E54G09). Effects on the stall limit of bleeding air from between stages of the compressor was explored by Mallett and Groesbeck (RM E55G27). A search for prestall warning signals is reported by Delio and Stiglic (RM E54I15). A control system using a stall detector was investigated by Novik, Heppler, and Stiglic (RM E55H03). A peak-holding control for maintaining maximum compressor discharge pressure during acceleration is analyzed by Delio (RM E56B10). Tests of a closed-loop control designed for following a temperature schedule during acceleration are described by Heppler, Stiglic and Novik (RM E56C08); a similar study for a schedule of maximum acceleration signal is presented by Stiglic, Heppler, and Novik (RM E56C07).

### Means for Avoiding Rotor Acceleration

Means for improving thrust control without changing engine rotor speed have been sought. Thrust reversers were explored by Povolny, Steffen, and McArdle (TN 3664). Compressor inlet throttling, coupled with opening the jet nozzle, was explored by Harp, Velie, and Mallett (RM E54F21).

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## FLAME-OUT

Flame-out occurs when combustion is inadvertently extinguished upon accelerating from cranking speed, when compressor surge is encountered, when quick changes in fuel flow are made, and when a high altitude and low engine speed are reached.

The limits of fuel flow above which flame-out occurs during acceleration are shown in a bench test of a combustor by Straight and McCafferty (RM E55G28) and by Friedman and Zettle (RM E54E11). Cases of flame-out resulting from compressor stall during acceleration are reported by Conrad, Bloomer, and Sobolewski (RM E51E08). Although carefully obtained records of deceleration, such as those of Vasu and Hinde have been examined (RM E52E23), very few have shown a lean mixture flame-out. Steady-state flame-out limits at altitudes from 5000 to 50,000 feet are shown by Bloomer (RM E9I26).

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Vasu, George, and Hinde, William L.: Effect of Engine and Control Limits on Steady-State and Transient Performance of Turbojet Engine with Variable-Area Exhaust Nozzle. NACA RM E52E23, 1953.

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#### TEMPERATURE CONTROL

Temperature-control problems that have been studied are correlation between blade-material temperature and gas-temperature sensing element, temperature distributions in passages where gas temperatures are measured, temperature during starting, and simultaneous control of temperature and speed. (Means for measuring gas temperature are treated in another section of this paper entitled SENSORS.)

Thermocouple measurements of turbine-blade temperature are reported by Farmer (RM E7L12). Experimental correlations between turbine-blade temperature and temperature-sensing stations that are practical for control are presented by Phillips (RM E55L22). This report describes effects of altitude on the correlations. Temperature distributions at the combustion-chamber outlet were surveyed by Mark and Zettle (RM E9I22) and by Zettle and Friedman (RM E54L21a). Combustor-liner temperatures are reported by Butze and Wear (RM E55A24). Turbine-disk temperatures are reported by Morse and Johnston (RM E54K30a).

Turbine-blade temperatures during starting were also observed by Morse and Johnston (RM E54K30a). Experimental and theoretical investigations of transient temperature throughout the turbine blade during starting are presented by Phillips (RM E55L22). This report also contains a map of engine acceleration as a function of gas temperature in the starting speed range.

A theoretical study of simultaneous control of turbine discharge-gas temperature and engine speed was made by Pack and Phillips (TN 3112). Some experimental data on the stability of a closed-loop control between turbine discharge temperature and fuel flow are presented by Heppler, Stiglic, and Novik (RM E56C08).

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Zettle, Eugene V., Norgren, Carl T., and Mark, Herman H.: Combustion Performance of Two Experimental Turbojet Annular Combustors at Conditions Simulating High-Altitude Supersonic Flight. NACA RM E54A15, 1954.

#### STABILITY AND DYNAMICS OF SMALL DISTURBANCES

The dynamics of a turbojet engine with fixed jet area was investigated by Craig, Vasu, and Schmidt (RM E53C17), and of a turbojet engine with variable jet area by Delio and Rosenzweig (RM E51K19). The high-frequency spectrum of engine dynamics was explored by Delio and Stiglic (RM E54I15). The law of similarity for estimating the effects of altitude pressure and temperature on engine time constant is given by Otto and Taylor (Rep. 1011). A method of estimating engine time constant was developed by Gold and Rosenzweig (RM E51K21). A convenient analog representation of the linear dynamics of a turbojet engine is presented by Ketchum and Craig (TN 2826). An experimental demonstration of the applicability of linear dynamic analysis to the design of speed control

is given by Dandois and Novik (TN 2642), and a similar demonstration for temperature control is given by Heppler, Stiglic, and Novik (RM E56C08). Test techniques and instrumentation for determining dynamic characteristics are described by Delio (TN 2634).

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#### COMBUSTION DYNAMICS

The frequency response of combustor pressure to disturbances in fuel flow to a turbojet engine can be found in a report by Delio and Stiglic (RM E54I15). An empirical transfer function for combustion dynamics was matched with experimental data on a turboprop engine by Craig, Nakanishi, and Wile (RM E55C23). The time delay in a turbojet-engine combustor response to change in fuel flow is shown by Heppler, Stiglic,

and Novik (RM E56C08). The effects of sinusoidally varying air flow on the combustion efficiency in a ram-jet combustor was explored by Dangle, Cervenka, and Perchonok (RM E54D01).

Data on dynamics of afterburner combustion are not available. Observations by Vasu, Wilcox, and Himmel (RM E54H10) on ram-jet combustors may be indicative of afterburner dynamics.

Further references of interest in connection with combustion dynamics will be found in the bibliography on fuel systems.

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## ENGINE INLET-DIFFUSER CONTROL

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## STEADY-STATE PERFORMANCE

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## FUEL SYSTEMS

Metering of fuel, distribution of fuel to several injection points, and transient response of fuel systems have been studied. Metering characteristics were explored by Gold and Straight (RM E8D14), and distribution by Straight and Gold (RM E50F05). Design formulas for constructing fuel systems having a specified transient response, together with illustrative experimental data, is given by Otto, Gold, and Hiller (TN 3445). Data on the transient behavior of fuel systems with duplex fuel nozzles is presented by McCafferty and Donlon (RM E55H03a). Observations of the transient response of fuel systems with long pipes are shown by Vasu, Wilcox, and Himmel (RM E54H10). Theoretical and experimental information on the transmission through a long hydraulic line is treated by Rothrock (Rep. 396).

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- Vasu, G., Wilcox, F. A., and Himmel, S. C.: Preliminary Report of Experimental Investigation of Ram-Jet Controls and Engine Dynamics. NACA RM E54H10, 1954.
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#### SENSORS

Sensors for measuring temperature, pressure, velocity or mass flow, fuel flow, engine acceleration, and engine thrust have been investigated.

#### Temperature

Reports on thermocouple design and accuracy have been prepared by Stickney (TN 3455) and Simmons (RM E54G22a). Theoretical and experimental information on thermocouple time response is presented by Scadron and Warshawsky (TN 2599). Means of electrical compensation to minimize the effects of thermocouple time delay are treated by Shepard and Warshawsky (TN 2703). Equipment for measuring turbine-blade temperature is described by Morse and Johnston (RM E54K30a).

### Pressure

A general and simplified treatment of the dynamic response of pressure sensors is described by Delio, Schwent, and Cesaro (TN 1988). Details of a pressure sensor capable of sensing pressures from zero to high frequency are presented by Patterson (TN 2659). Delio and Stiglic (RM E54I15) and Vasu, Wilcox, and Himmel (RM E54H10) give the measured frequency responses of several pressure sensors.

### Air and Fuel Flow

Design and test of a hot-wire anemometer suitable for measuring rapidly changing air flow are reported by Shepard (TN 3406). Delio and Schwent (RM E51D27) describe a fuel-flow sensor suitable for measuring fluctuating fuel flows.

### Engine Acceleration

Measurement and recording of engine acceleration are described by Schmidt, Vasu, and McGraw (RM E53B10).

### Engine Thrust

A thrust sensor suitable for flight testing is described by Fleming and Gabriel (RM E55D05a), and one suitable for laboratory use is described by Delio and Schwent (RM E51D27).

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### GENERAL CONTROL SYSTEM THEORY

The general areas in which research has been done on control systems are definition and selection of optimum controls, multiple-loop controls, peak-holding or optimizing controls, control with saturation effects, on-off controls, and dynamic description of physical systems.

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#### Optimum Controls

Boksenbom and Hood (Rep. 1068) propose that an optimum control minimize certain integrals that are indicative of disadvantages such as accumulation of damage or loss of impulse. They apply variational methods to specify the analytical form as well as the coefficients for the control. Examples for controlling one manipulated variable are given. Experimental application of this approach is reported by Dandois and Novik (TN 2642). A tentative extension of the theory to multiple-loop controls is presented by Boksenbom, Novik, and Heppler (TN 2939).

A satisfactory period of damping is chosen as a criterion for control adjustment by Sternfield and Gates (TN 1859), and a method for selecting the coefficients of the differential equations of motion to satisfy the criterion is devised for an aircraft.

#### Multiple-Loop Controls

Multiple-loop controls are applicable where several manipulated variables exist and several output variables must be constrained. Boksenbom and Hood (Rep. 980) outline a general method of selecting a control that will permit changing one output by simultaneous manipulation of all manipulated variables in such a manner that the other output variables (to a total of one less than the manipulated variables) do not change during the transient. Pack and Phillips (Rep. 1212) present an analog study of the application of this control principle to the control of a turbojet engine, where engine speed and turbine gas temperature are constrained simultaneously.

#### Peak-Holding or Optimizing Controls

Specific applications of the principles of peak-holding controls have been explored. Delio and Stiglic (RM E54115) present experimental data on acceleration characteristics of an engine together with a discussion of applications of a peak-holding control for acceleration.

Novik, Heppler, and Stiglic (RM E55H03) present experimental results of a control designed to hold peak pressure in the compressor during acceleration. Delio (RM E56B10) made an analog study of a peak-holding control for the case of a system showing a discontinuity in the region of the peak of its characteristics. Vasu, Wilcox, and Himmel (RM E54H10) show experimental operation of a peak-holding control for regulation of the performance of a ram-jet engine.

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